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AUTHOR Swedler, James A.  
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## ABSTRACT

This game is designed to be used in junior and senior high school science classes with the purpose of introducing quark theory to students. This material expands on atomic theory and subatomic structure. Quarks are the fundamental building blocks of protons and neutrons. The game will teach students about the standard model of elementary particles, quarks, their symbols, masses, and charges. The game has four parts: (1) build a meson; (2) build a baryon; (3) decode a meson; and (4) decode a baryon. This guide provides worksheets to be used during a five-day period. This game does not include the property of spin in describing mesons and baryons. (Author/YP)

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b t d

THE BOX  
QUARK OF  
BOX QUARKS

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Dr. J. SWEDLER

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157 N. ROOT  
AURORA, IL 60503

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# THE QUARK BOX

by

Dr. James A. Swedler

## INTRODUCTION

Today we are going to talk about the elementary particles that make up the world. We already know that everything is made up of atoms, tiny particles that are too small to be seen by themselves. There are 92 different kinds of naturally occurring atoms that we call elements, from Hydrogen to Uranium. They make up everything in the universe, the stars, the air, the earth, and even us.

We also know that atoms are made up of different parts: electrons, protons, and neutrons. The electrons spin around the nucleus; and the nucleus is made up of protons and neutrons. This is what scientists have known since the 1930's about matter. In the past fifty years physicists and chemists have been studying atoms very intently. They have been digging deeper into atoms to understand how they behave; and to find out everything there is to know about them.

We will discuss what physicists have discovered about atoms, and a little about how this knowledge came about. What they found does not change anything you already know about atoms, it just adds to it.

## HOW PHYSICISTS FOUND QUARKS

Atoms are very tiny. They are so small that you cannot see them; and they are too light to weigh individually on any scale.

Scientists have to use special machines to study atoms. To see atoms, scientists use high powered electron microscopes. An electron microscope magnifies things so they look thousands of times larger. A quarter magnified in an electron microscope would be over a mile long! Just looking at atoms with an electron microscope does not tell you a lot about them, so physicists use another machine to study atoms: accelerators.

Charged subatomic particles, protons (+) and electrons (-), will travel very fast in an electrical field. An accelerator takes protons or electrons and speeds them up to very high speeds. Then they are crashed into targets of other atoms to see what occurs in the collision. It is kind of like hitting a watch with a hammer and studying how it works from the pieces that come flying out. This may seem like a strange way to study protons, but this is the only way physicsists can study them. Protons travel very fast. Race cars that travel over 200 miles per hour are slow compared to protons. A Jet fighter travelling over 2,000 miles per hour is slow compared to protons. Protons travel so fast they record their speed in miles per second. The purpose of an accelerator is to get a proton travelling as fast as it can. The upper limit of a proton's speed is the speed of light. The speed of light is 186,000 miles per second. For example, the sun is 93,500,000 miles from earth. The light produced by the sun travels to us in just 8 minutes and 20 seconds. A 2,000 mile per hour jet would take 46,750 hours to travel that distance.

Physicists accelerate protons by putting them in electrical fields which are measured in electron volts (eV). An electron

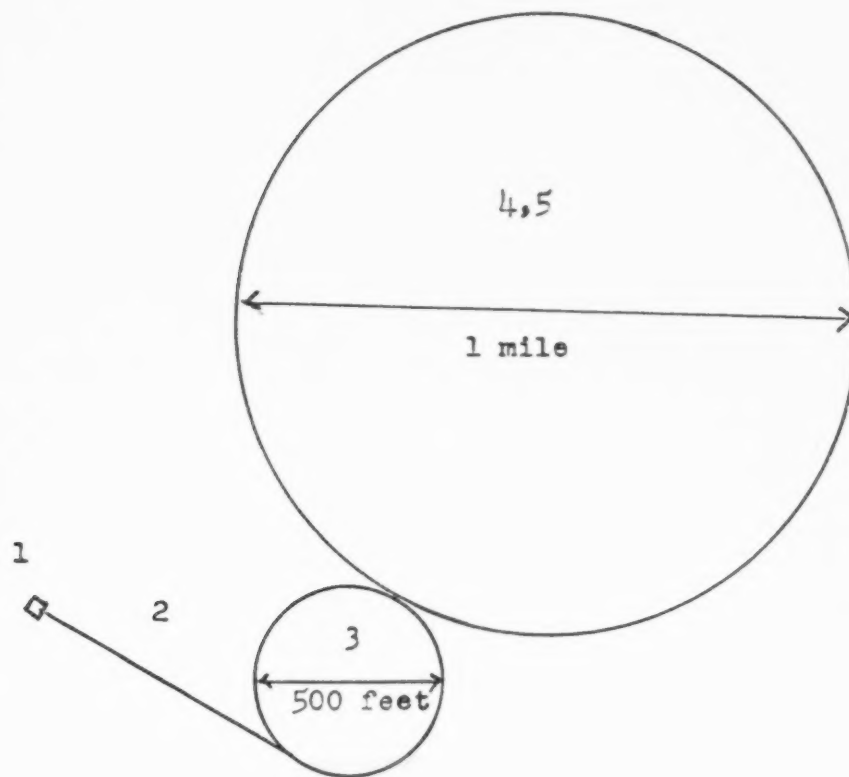
volt has enough energy to send a proton off at 8.6 miles per second, (3,960 miles per hour). The prefixes for electron volts at higher power are:

- 1 KeV = one thousand electron volts
- 1 MeV = one million electron volts
- 1 GeV = one billion electron volts
- 1 TeV = one trillion electron volts.

How a proton is accelerated to nearly the speed of light can be shown by explaining how Fermi National Accelerator Laboratory in Batavia, Illinois works. The Fermilab accelerator speeds up protons in 5 steps similar to how a car shifts from low gear to high gear. It takes protons from rest to a speed of over 185,000 miles per second. (see figure 1)

- 1) The first step in the Fermilab accelerator is the Cockcroft-Walton generator. It takes Hydrogen gas and adds electrons to it making hydrogen ions (a proton plus two electrons). These ions are delivered to the Linac at 750 KeV (750,000 eV).
- 2) The Linac is a linear accelerator 500 feet long that takes the hydrogen ions and accelerates them to 200 MeV (200 million eV). They are then injected into the Booster.
- 3) The Booster is about 500 feet in diameter and strips the electrons from the hydrogen ions, leaving just the positively charged protons. The Booster accelerates the protons to 8 GeV (8 billion eV).

Figure 1  
Fermilab Accelerators



| <u>No.</u> | <u>Accelerator</u>         | <u>(length, voltage)</u> |
|------------|----------------------------|--------------------------|
| 1          | Cockcroft-Walton Generator | (—, 750 KeV)             |
| 2          | Linac                      | (500 feet, 200 MeV)      |
| 3          | Booster                    | (.3 mile, 8 GeV)         |
| 4          | Main Ring                  | (4 miles, 150 GeV)       |
| 5          | Tevatron                   | (4 miles, 1 TeV)         |

4) The proton beam is injected into the main ring where the protons spend the next 5 seconds. The main ring is four miles in circumference and has 1,000 water-cooled magnets. The magnets bend and focus the proton beam so it keeps travelling in a circle. The beam is accelerated every time it goes around the ring by radio frequency (RF) cavities that give the protons more energy. The RF cavities add 3 MeV to the protons every time they go around the ring. The protons travel around the ring 47,000 times a second; that is 188,000 miles, the distance from the earth to the moon. In five seconds it reaches an energy of 150 GeV.

5) The protons are then injected into the Tevatron. The Tevatron is a superconducting magnet ring directly underneath the main ring. Its 1,000 magnets are cooled to -452 degrees Fahrenheit by liquid Helium. The Tevatron uses less electricity than the main ring even though it is 2.5 times more powerful than the main ring. In the Tevatron, the proton beam is accelerated to 1 TeV (1,000 billion eV).

Finally, the protons are ready for a physics experiment. Travelling at over 185,000 miles per second, they collide with other protons and produce a large number of different products.

#### WHAT ARE QUARKS?

The results of thousands of high energy particle physics experiments have been analyzed over the past 50 years. Physicists have developed a theory called the standard model of elementary

particles to explain their results . It starts with a picture of the present universe. (see figure 2) The up and down quarks are never seen alone. They are found in sets of three in the proton and neutron. The neutrino does not interact with atoms but flies around the universe on its own. The quarks have charges that are not whole numbers: up ( $+2/3$ ), down ( $-1/3$ ). They combine together to form the protons and neutrons that make up the nuclei of atoms. (see figure 3) The proton is made up of 2 up quarks and 1 down quark. The charges of  $+2/3$ ,  $+2/3$ , and  $-1/3$  make a total charge of  $+1$ , the charge of a proton. The neutron is made up of 1 up quark and 2 down quarks. The charges of  $+2/3$ ,  $-1/3$ , and  $-1/3$  make a total charge of 0, the charge of a neutron. What holds the quarks together is the carrier of the strong force: the gluon. Gluons carry color between the quarks. The three colors are red, blue, and green. The color rule is that the total color must be white. This is done by having one red, one blue, and one green quark.

High energy collisions produce quarks from other generations of matter. (see figure 4) The present universe is made up of generation I quarks. Heavier quarks are found in generations II and III. The extra mass produced in some reactions comes from high energies given the protons in accelerators. It follows from Einstein's equation  $E = mc^2$ . This equation tells us that energy and mass are interchangeable. In a high energy collision energy can be converted into mass; allowing charm, strange, bottom, and top quarks to appear.

Figure 2  
The Present Universe

|         |                           |                   |                            |
|---------|---------------------------|-------------------|----------------------------|
| Quarks  |                           | I                 |                            |
|         |                           | Up                |                            |
|         | <b>u</b>                  | $+\frac{2}{3}$    | $\frac{R, G, B}{\sim 310}$ |
|         |                           | Down              |                            |
|         | <b>d</b>                  | $-\frac{1}{3}$    | $\frac{R, G, B}{\sim 310}$ |
| Leptons |                           | Electron          |                            |
|         |                           | <b>e</b>          | $-1$<br>$.511$             |
|         |                           | Electron Neutrino |                            |
|         | <b><math>\nu_e</math></b> | $0$               | $\sim 0$                   |

By definition Quarks respond to the strong force (gluons). Leptons do not respond to the strong force.

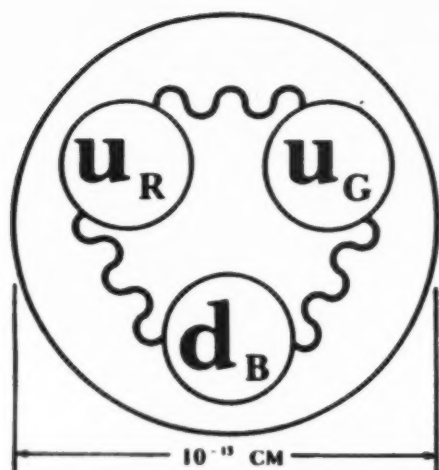
### Legend

|        |          |                            |                                 |
|--------|----------|----------------------------|---------------------------------|
|        |          | I Generation               |                                 |
| Name   | Up       |                            |                                 |
|        | <b>u</b> | $+\frac{2}{3}$             | Charge                          |
|        |          | $\frac{R, G, B}{\sim 310}$ | Color                           |
| Symbol |          |                            | Rest Mass<br>MeV/c <sup>2</sup> |
|        |          | Colors                     |                                 |
|        |          | R = Red                    |                                 |
|        |          | G = Green                  |                                 |
|        |          | B = Blue                   |                                 |
|        |          | C = Cyan                   |                                 |
|        |          | M = Magenta                |                                 |
|        |          | Y = Yellow                 |                                 |

Figure 3

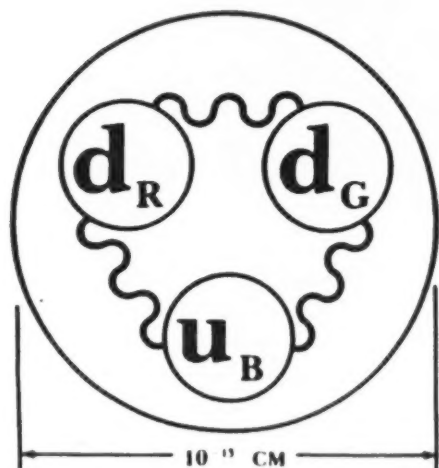
Quark Structure of the Proton and Neutron

Standard Model of the Proton



| Quarks | Color | Charge | Rest Mass<br>MeV/c <sup>2</sup> |
|--------|-------|--------|---------------------------------|
| Up     | Red   | + 2/3  | ~ 310                           |
| Up     | Green | + 2/3  | ~ 310                           |
| Down   | Blue  | - 1/3  | ~ 310                           |
| Proton | White | + 1    | 938                             |

Standard Model of the Neutron



| Quarks  | Color | Charge | Rest Mass<br>MeV/c <sup>2</sup> |
|---------|-------|--------|---------------------------------|
| Down    | Red   | - 1/3  | ~ 310                           |
| Down    | Green | - 1/3  | ~ 310                           |
| Up      | Blue  | + 2/3  | ~ 310                           |
| Neutron | White | 0      | 940                             |

Legend


 Quarks  
 Gluons

Colors  
 R = Red  
 B = Blue  
 G = Green

Figure 4  
The Three Generations of Matter

|         |                   | Matter                                                        |                                                         |                                                                |
|---------|-------------------|---------------------------------------------------------------|---------------------------------------------------------|----------------------------------------------------------------|
|         |                   | I                                                             | II                                                      | III                                                            |
| Quarks  | Up                | $\bar{u}$ $\frac{+\frac{2}{3}}{\text{R, G, B}}$<br>$\sim 310$ | $\bar{c}$ $\frac{+\frac{2}{3}}{\text{R, G, B}}$<br>1500 | $\bar{t}$ $\frac{+\frac{2}{3}}{\text{R, G, B}}$<br>$> 22500$   |
|         | Down              | $\bar{d}$ $\frac{-\frac{1}{3}}{\text{R, G, B}}$<br>$\sim 310$ | $\bar{s}$ $\frac{-\frac{1}{3}}{\text{R, G, B}}$<br>505  | $\bar{b}$ $\frac{-\frac{1}{3}}{\text{R, G, B}}$<br>$\sim 5000$ |
| Leptons | Electron          | $e$ $\frac{-1}{.511}$                                         | $\mu$ $\frac{-1}{106.6}$                                | $\tau$ $\frac{-1}{1784}$                                       |
|         | Electron Neutrino | $\nu_e$ $\frac{0}{\sim 0}$                                    | $\nu_\mu$ $\frac{0}{\sim 0}$                            | $\nu_\tau$ $\frac{0}{< 70}$                                    |
|         |                   |                                                               |                                                         |                                                                |

The different kinds of quark particles that come out of high energy collisions fall into two classes: baryons and mesons. Baryons contain three quarks. The proton and neutron are baryons. Using all six quarks there are 56 possible baryons. The meson is a quark-anti-quark system. Anti-quarks are just like quarks except that they have the opposite charge and anti-color of their quarks. (see figure 5) The anti-up has a charge of  $-2/3$  and its colors are: cyan (anti-red), magenta (anti-green), and yellow (anti-blue). Anti-up's mass is 310 MeV, the same as the up quark. There are 36 possible mesons that can exist from all the possible combinations of a quark and an anti-quark. Mesons annihilate very quickly to form energy (photons, x-rays) but they do form a stable structure that exists for a fraction of a second.

Figure 5  
The Three Generations of Antimatter

|             |                       | Antimatter                                  |                                         |                                              |
|-------------|-----------------------|---------------------------------------------|-----------------------------------------|----------------------------------------------|
|             |                       | I                                           | II                                      | III                                          |
| Antiquarks  | Anti Up               | $\bar{u}$ $\frac{-2/3}{C, M, Y}$ $\sim 310$ | $\bar{c}$ $\frac{-2/3}{C, M, Y}$ $1500$ | $\bar{t}$ $\frac{-2/3}{C, M, Y}$ $> 22500$   |
|             | Anti Down             | $\bar{d}$ $\frac{+1/3}{C, M, Y}$ $\sim 310$ | $\bar{s}$ $\frac{+1/3}{C, M, Y}$ $505$  | $\bar{b}$ $\frac{+1/3}{C, M, Y}$ $\sim 5000$ |
| Antileptons | Positron              | $e^+$ $\frac{+1}{.511}$                     | $\bar{\mu}$ $\frac{+1}{106.6}$          | $\bar{\tau}$ $\frac{+1}{1784}$               |
|             | Electron Antineutrino | $\bar{\nu}_{e^+}$ $\frac{0}{\sim 0}$        | $\bar{\nu}_{\mu}$ $\frac{0}{\sim 0}$    | $\bar{\nu}_{\tau}$ $\frac{0}{< 70}$          |
|             |                       |                                             |                                         |                                              |

Additional Particle Physics References:

"Worlds Within The Atom" by John Boslough National Geographic.

May 1985, pp. 634-642, 649-663.

"The Story of Creation" by Timothy Ferris, PBS Nov 20, 1985. 90

minute videotape (two - 45 minutes segments.)

THE QUARK BOX  $\rightleftharpoons$  BOX OF QUARKS  
by

Dr. James A. Swedler

This game is designed to be used with a unit on particle physics. It could be used by itself if the students are given a presentation on particle physics and the standard model of elementary particles.

The Quark Box is designed for Junior High school students.\* Its purpose is to give students an opportunity to work with the 12 quarks and antiquarks in building and decoding meson and baryon structures. It will provide students with a working knowledge of the Elementary Particle Table. Specifically the names and symbols for the 6 quarks and 6 antiquarks, the charge and mass values for these particles, and practice in building mesons and baryons. Worksheets are also available for decoding meson and baryon particle structure from their total mass and charge values.

A possible sequence for using The Quark Box.

- Day 1      Presentation on particle physics and the standard model.
- Day 2      Build a Meson. Build a Baryon. Give examples of each. Have each lab group (2 students) build 8 mesons and 8 baryons.
- Day 3      Decode a Meson. Do two examples and have each lab group decode 4 or 8 mesons. This assignment can be graded. It can also be arranged so that every lab group can be working on different worksheets.
- Day 4      Decode a baryon. Do two examples and have each lab group decode 4 baryons.
- Day 5      (optional) Test on materials from days 1-4.
  - ie: - finding information from the particle table.
  - given the particles of a meson & baryon compute the total mass and charge.
  - decode a meson & baryon from its total mass and charge.

Note: This game does not include the property of spin in describing mesons and baryons. This property is left for more advanced students.

\* Math requirement: Students must be able to add positive and negative fractions.

### THE BUILDING GAMES:

The deck of cards consists of 36 cards: 18 quark cards, and 18 anti-quark cards. The cards can be of any size, 3"x 5" file cards work very well.

The 18 quark cards are divided into 3 color groups. One set each of 6 red, blue, and green cards. Each set has one each of: u, d, c, s, b, t.

The 18 antiquark cards are divided into 3 anticolor groups. One each of 6 cyan, magenta, & yellow cards. Each set has one each of:  $\bar{u}$ ,  $\bar{d}$ ,  $\bar{c}$ ,  $\bar{s}$ ,  $\bar{b}$ ,  $\bar{t}$ .

The cards only have the symbols of the quarks & antiquarks on them.

### BUILD A MESON

1. Divide your deck of cards into the quarks and antiquarks. Shuffle each half.
2. A meson is a quark, antiquark system. To build a meson select a card from each half: one quark, and one antiquark. Write the symbol of your quark and antiquark on your worksheet.
3. Go to the elementary particle table and write the name, charge, and mass for the particles in your meson. Calculate the total charge and mass for your meson.
4. After the students have completed their worksheets give them the meson dictionary. Have them find the mesons they have built and determine the ones that have names. Write the names on the worksheets. They can check the total mass and charge with their calculations.
5. Reshuffle your quarks & antiquarks periodically.

### BUILD A BARYON

1. Divide your quark cards into 3 groups by color: red, blue, and green. (You can divide your antiquarks into their 3 anticolors: cyan, magenta, and yellow; and build anti-baryons by following these same rules).

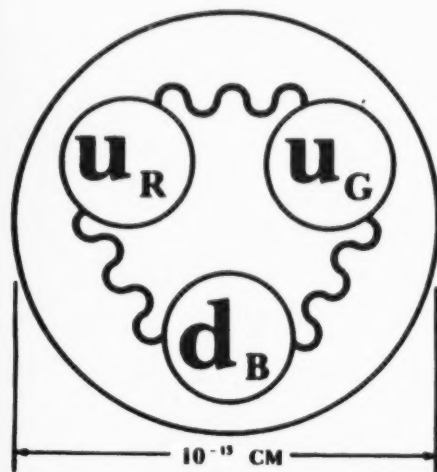
2. A baryon has 3 quarks. One each of the three colors: red, blue, and green. They add up to white, the color of a baryon. Select one card from each color of quarks. Write the symbols of your quarks on the worksheet.
3. Go to the Elementary Particle Table and write out the name, charge, and mass for the three quarks in your baryon. Calculate the total mass and charge of your baryon.
4. After finishing the worksheets, give the students the baryon dictionary. Have them find the baryons they built and write their names on the worksheet. Check the mass and charge with their calculations.
5. Reshuffle your color sets periodically.

# Standard Model of Elementary Particles

| Matter  |                        |  |  |                        |  |  |                        |  |  | Antimatter             |  |  |                        |  |  |                        |  |  |  |
|---------|------------------------|--|--|------------------------|--|--|------------------------|--|--|------------------------|--|--|------------------------|--|--|------------------------|--|--|--|
| I       |                        |  |  |                        |  |  |                        |  |  | II                     |  |  |                        |  |  |                        |  |  |  |
| III     |                        |  |  |                        |  |  |                        |  |  | I                      |  |  |                        |  |  |                        |  |  |  |
| Quarks  | Up                     |  |  | Charm                  |  |  | Top/Truth              |  |  | Anti Up                |  |  | Anti Charm             |  |  | Anti Top/Truth         |  |  |  |
|         | $\frac{+2/3}{R, G, B}$ |  |  | $\frac{+2/3}{R, G, B}$ |  |  | $\frac{+2/3}{R, G, B}$ |  |  | $\frac{-2/3}{C, M, Y}$ |  |  | $\frac{-2/3}{C, M, Y}$ |  |  | $\frac{-2/3}{C, M, Y}$ |  |  |  |
|         | $\sim 310$             |  |  | 1500                   |  |  | > 22500                |  |  | $\sim 310$             |  |  | 1500                   |  |  | > 22500                |  |  |  |
|         | Down                   |  |  | Strange                |  |  | Bottom/Beauty          |  |  | Anti Down              |  |  | Anti Strange           |  |  | Anti Bottom/Beauty     |  |  |  |
|         | $\frac{-1/3}{R, G, B}$ |  |  | $\frac{-1/3}{R, G, B}$ |  |  | $\frac{-1/3}{R, G, B}$ |  |  | $\frac{+1/3}{C, M, Y}$ |  |  | $\frac{+1/3}{C, M, Y}$ |  |  | $\frac{+1/3}{C, M, Y}$ |  |  |  |
|         | $\sim 310$             |  |  | 505                    |  |  | $\sim 5000$            |  |  | $\sim 310$             |  |  | 505                    |  |  | $\sim 5000$            |  |  |  |
| Leptons | Electron               |  |  | Muon                   |  |  | Tau                    |  |  | Positron               |  |  | Antimuon               |  |  | Antitau                |  |  |  |
|         | $\frac{-1}{.511}$      |  |  | $\frac{-1}{106.6}$     |  |  | $\frac{-1}{1784}$      |  |  | $\frac{+1}{.511}$      |  |  | $\frac{+1}{106.6}$     |  |  | $\frac{+1}{1784}$      |  |  |  |
|         | Electron Neutrino      |  |  | Muon Neutrino          |  |  | Tau Neutrino           |  |  | Electron Antineutrino  |  |  | Muon Antineutrino      |  |  | Tau Antineutrino       |  |  |  |
|         | $\frac{0}{\sim 0}$     |  |  | $\frac{0}{\sim 0}$     |  |  | $\frac{0}{< 70}$       |  |  | $\frac{0}{\sim 0}$     |  |  | $\frac{0}{\sim 0}$     |  |  | $\frac{0}{< 70}$       |  |  |  |
|         | $\nu_e$                |  |  | $\nu_\mu$              |  |  | $\nu_\tau$             |  |  | $\bar{\nu}_{e^+}$      |  |  | $\bar{\nu}_\mu$        |  |  | $\bar{\nu}_\tau$       |  |  |  |
|         | $\sim 0$               |  |  | $\sim 0$               |  |  | $< 70$                 |  |  | $\sim 0$               |  |  | $\sim 0$               |  |  | $< 70$                 |  |  |  |

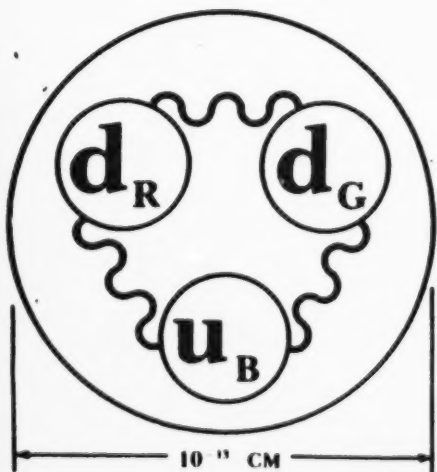
| Gauge Bosons      |               |                  |        |      |                   |           |               |        | Legend       |                        |  |          |             |                  |  |  |  |  |
|-------------------|---------------|------------------|--------|------|-------------------|-----------|---------------|--------|--------------|------------------------|--|----------|-------------|------------------|--|--|--|--|
| Force             | Force Carrier | Rest Mass GeV/c² | Charge | Spin | Relative Strength | Range     | Color         |        | I Generation |                        |  |          | Colors      |                  |  |  |  |  |
| Strong            | Gluons        | 0                | 0      | 1    | 1                 | <10⁻¹⁵ cm | Yes           |        | Name         | Up                     |  |          |             | Charge           |  |  |  |  |
| Weak              | W⁺            | 81               | +1     | 1    | 10⁻¹⁷             | <10⁻¹⁶ cm | Color Neutral | Symbol | u            | $\frac{+2/3}{R, G, B}$ |  |          |             | Color            |  |  |  |  |
|                   | W⁻            | 81               | -1     | 1    |                   |           |               |        |              | $\sim 310$             |  |          |             | Rest Mass MeV/c² |  |  |  |  |
|                   | Z⁰            | 93               | 0      | 1    |                   |           |               |        |              |                        |  |          |             |                  |  |  |  |  |
| Electro-Magnetism | Photons       | 0                | 0      | 1    | 10⁻²              | Infinite  | Color Neutral |        |              |                        |  |          |             | R = Red          |  |  |  |  |
| Gravity           | Graviton      | 0                | 0      | 2    | 10⁻³⁸             | Infinite  | Color Neutral |        |              |                        |  |          |             | G = Green        |  |  |  |  |
|                   |               |                  |        |      |                   |           |               |        |              |                        |  | C = Cyan |             |                  |  |  |  |  |
|                   |               |                  |        |      |                   |           |               |        |              |                        |  |          | M = Magenta |                  |  |  |  |  |
|                   |               |                  |        |      |                   |           |               |        |              |                        |  |          | Y = Yellow  |                  |  |  |  |  |

## Standard Model of the Proton



| Quarks | Color | Charge         | Rest Mass MeV/c <sup>2</sup> |
|--------|-------|----------------|------------------------------|
| Up     | Red   | $+\frac{2}{3}$ | $\sim 310$                   |
| Up     | Green | $+\frac{2}{3}$ | $\sim 310$                   |
| Down   | Blue  | $-\frac{1}{3}$ | $\sim 310$                   |
| Proton | White | $+1$           | 938                          |

## Standard Model of the Neutron



| Quarks  | Color | Charge         | Rest Mass MeV/c <sup>2</sup> |
|---------|-------|----------------|------------------------------|
| Down    | Red   | $-\frac{1}{3}$ | $\sim 310$                   |
| Down    | Green | $-\frac{1}{3}$ | $\sim 310$                   |
| Up      | Blue  | $+\frac{2}{3}$ | $\sim 310$                   |
| Neutron | White | 0              | 940                          |

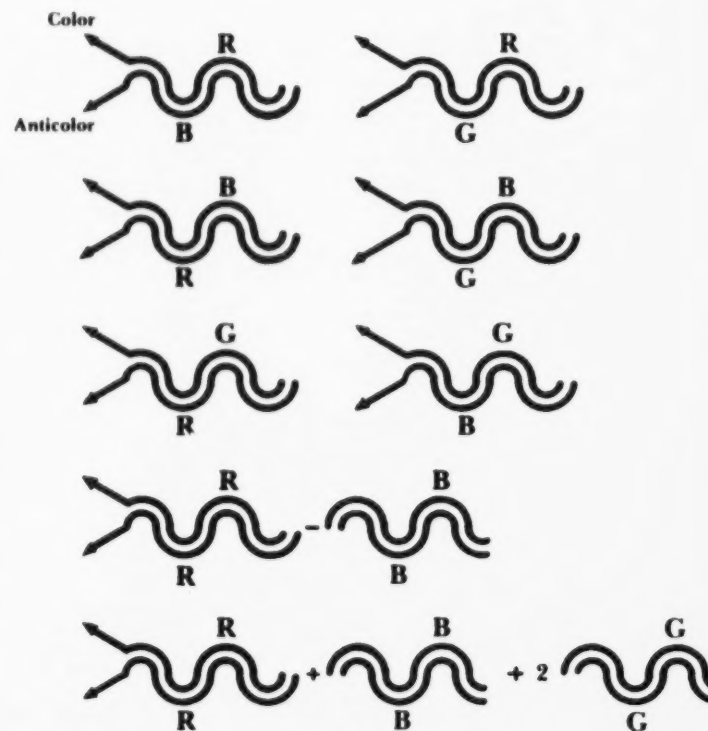
### Legend

Quarks  
 Gluons

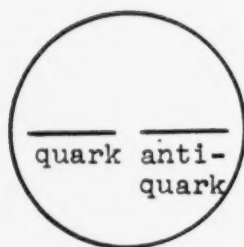
Colors  
 R = Red  
 B = Blue  
 G = Green

## Gluons

- Transfer color between quarks
- Hold quarks together
- 8 Types



# BUILD A MESON



Particle  
Name

Charge

Mass  
MeV

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

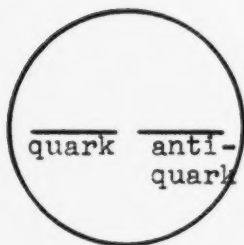
\_\_\_\_\_

Total:

=====

=====

\_\_\_\_\_  
Name?



Particle  
Name

Charge

Mass  
MeV

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

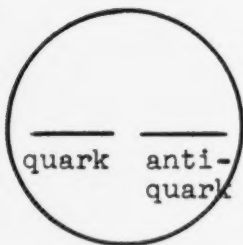
\_\_\_\_\_

Total:

=====

=====

\_\_\_\_\_  
Name?



Particle  
Name

Charge

Mass  
MeV

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

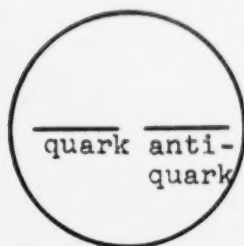
\_\_\_\_\_

Total:

=====

=====

\_\_\_\_\_  
Name?



Particle  
Name

Charge

Mass  
MeV

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

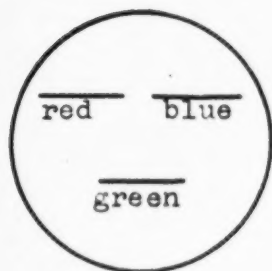
Total:

=====

=====

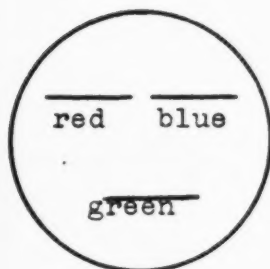
\_\_\_\_\_  
Name?

# BUILD A BARYON



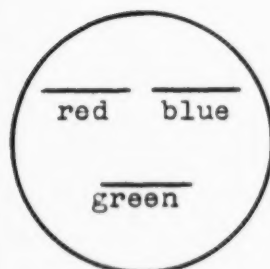
| Particle Name | Color        | Charge | Mass MeV |
|---------------|--------------|--------|----------|
| _____         | <u>red</u>   | _____  | _____    |
| _____         | <u>blue</u>  | _____  | _____    |
| _____         | <u>green</u> | _____  | _____    |
| Total:        | <u>white</u> | =====  | =====    |

\_\_\_\_\_  
Name?



| Particle Name | Color        | Charge | Mass MeV |
|---------------|--------------|--------|----------|
| _____         | <u>red</u>   | _____  | _____    |
| _____         | <u>blue</u>  | _____  | _____    |
| _____         | <u>green</u> | _____  | _____    |
| Total:        | <u>White</u> | =====  | =====    |

\_\_\_\_\_  
Name?



| Particle Name | Color        | Charge | Mass MeV |
|---------------|--------------|--------|----------|
| _____         | <u>red</u>   | _____  | _____    |
| _____         | <u>blue</u>  | _____  | _____    |
| _____         | <u>green</u> | _____  | _____    |
| Total:        | <u>White</u> | =====  | =====    |

\_\_\_\_\_  
Name?



| Particle Name | Color        | Charge | Mass MeV |
|---------------|--------------|--------|----------|
| _____         | <u>red</u>   | _____  | _____    |
| _____         | <u>blue</u>  | _____  | _____    |
| _____         | <u>green</u> | _____  | _____    |
| Total:        | <u>White</u> | =====  | =====    |

\_\_\_\_\_  
Name?

# DECODE A MESON

Example: Charge: -1  
Mass: 2,005 MeV

1. Take the total mass and look on your elementary particle table for the possible combinations of masses that would add up to 2,005.

It must include:  $c$  or  $\bar{c}$  1,500  
 $s$  or  $\bar{s}$  505  
2,005

2. In order to find which combination of quark and antiquark your meson is you need to use the total charge. (-1)

(if there is no d or u present there will be only two charge combinations)

$$\begin{array}{rcl} c & +2/3 & \bar{c} & -2/3 \\ \bar{s} & +1/3 & s & -1/3 \\ \hline & +1 & & -1 \end{array}$$

The answer is  $\bar{c} s$ .

3. Go to the meson table to check your work. Write the name of the meson on your worksheet.

Example: Charge: +1  
Mass: 815 MeV

1. Take the total mass and look on your elementary particle table for the possible combinations of masses that would add up to 815.

It must include:  $u, d$  or  $\bar{u}, \bar{d}$  310  
 $s$  or  $\bar{s}$  505  
815

2. In order to find which combination of quark and antiquark your meson is you need to use the total charge. (+1)

(If there is a u or d present; there will be four possible charge combinations)

$$\begin{array}{rclcl} u & +2/3 & d & -1/3 & \bar{u} & -2/3 & \bar{d} & +1/3 \\ \bar{s} & +1/3 & \bar{s} & +1/3 & s & -1/3 & s & -1/3 \\ \hline & +1 & & 0 & & -1 & & 0 \end{array}$$

The answer is  $u \bar{s}$

3. Go to the meson table to check your work. Write the name of the meson on your worksheet.

# DECODE A MESON

1

|                     | Mass<br>MeV | Charge | Quarks |
|---------------------|-------------|--------|--------|
| Charge <u>-1</u>    | _____       | _____  | _____  |
| Mass <u>815</u> MeV | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>0</u>       | _____       | _____  | _____  |
| Mass <u>3,000</u> MeV | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>+1</u>      | _____       | _____  | _____  |
| Mass <u>2,005</u> MeV | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                        | Mass<br>MeV | Charge | Quarks |
|------------------------|-------------|--------|--------|
| Charge <u>-1</u>       | _____       | _____  | _____  |
| Mass <u>22,810</u> MeV | _____       | _____  | _____  |



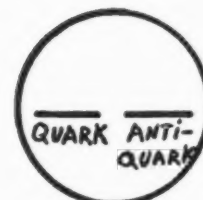
Name: \_\_\_\_\_

# DECODE A MESON

2

Charge +1      Mass MeV      Charge      Quarks

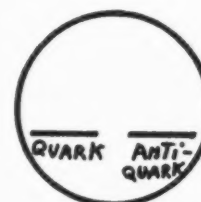
Mass 620 MeV



Name: \_\_\_\_\_

Charge -1      Mass MeV      Charge      Quarks

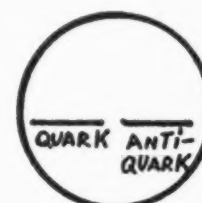
Mass 6,500 MeV



Name: \_\_\_\_\_

Charge 0      Mass MeV      Charge      Quarks

Mass 1,010 MeV



Name: \_\_\_\_\_

Charge +1      Mass MeV      Charge      Quarks

Mass 5,310 MeV

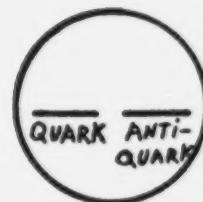


Name: \_\_\_\_\_

# DECODE A MESON

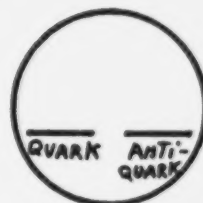
3

|                     | Mass<br>MeV       | Charge            | Quarks            |
|---------------------|-------------------|-------------------|-------------------|
| Charge <u>-1</u>    | <u>          </u> | <u>          </u> | <u>          </u> |
| Mass <u>620</u> MeV | <u>          </u> | <u>          </u> | <u>          </u> |



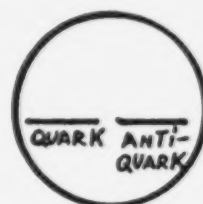
Name:                     

|                     | Mass<br>MeV       | Charge            | Quarks            |
|---------------------|-------------------|-------------------|-------------------|
| Charge <u>+1</u>    | <u>          </u> | <u>          </u> | <u>          </u> |
| Mass <u>815</u> MeV | <u>          </u> | <u>          </u> | <u>          </u> |



Name:                     

|                        | Mass<br>MeV       | Charge            | Quarks            |
|------------------------|-------------------|-------------------|-------------------|
| Charge <u>+1</u>       | <u>          </u> | <u>          </u> | <u>          </u> |
| Mass <u>27,500</u> MeV | <u>          </u> | <u>          </u> | <u>          </u> |



Name:                     

|                     | Mass<br>MeV       | Charge            | Quarks            |
|---------------------|-------------------|-------------------|-------------------|
| Charge <u>0</u> *   | <u>          </u> | <u>          </u> | <u>          </u> |
| Mass <u>620</u> MeV | <u>          </u> | <u>          </u> | <u>          </u> |



Name:                     

\* TWO ANSWERS

# DECODE A MESON

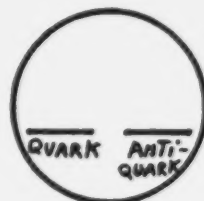
4

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>+1</u>      | _____       | _____  | _____  |
| Mass <u>1,810</u> MeV | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>-1</u>      | _____       | _____  | _____  |
| Mass <u>2,005</u> MeV | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                        | Mass<br>MeV | Charge | Quarks |
|------------------------|-------------|--------|--------|
| Charge <u>-1</u>       | _____       | _____  | _____  |
| Mass <u>23,005</u> MeV | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                        | Mass<br>MeV | Charge | Quarks |
|------------------------|-------------|--------|--------|
| Charge <u>0</u> *      | _____       | _____  | _____  |
| Mass <u>24,000</u> MeV | _____       | _____  | _____  |



Name: \_\_\_\_\_

\*TWO ANSWERS

# DECODE A MESON

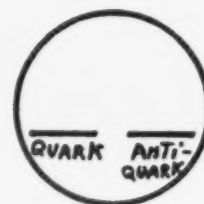
5

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>-1</u>      | _____       | _____  | _____  |
| Mass <u>5,310</u> MeV | _____       | _____  | _____  |



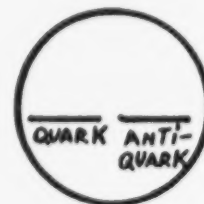
Name: \_\_\_\_\_

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>+1</u>      | _____       | _____  | _____  |
| Mass <u>6,500</u> MeV | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                        | Mass<br>MeV | Charge | Quarks |
|------------------------|-------------|--------|--------|
| Charge <u>-1</u>       | _____       | _____  | _____  |
| Mass <u>27,500</u> MeV | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>0*</u>      | _____       | _____  | _____  |
| Mass <u>5,505</u> MeV | _____       | _____  | _____  |



Name: \_\_\_\_\_

\*TWO ANSWERS

DECODE A MESON

Answers to Worksheets 1 to 5

| <u>Page</u> | <u>Number</u> | <u>Charge</u> | <u>Mass</u> | <u>Answer</u>          |
|-------------|---------------|---------------|-------------|------------------------|
| 1           | 1             | -1            | 815         | $s \bar{u}$            |
|             | 2             | 0             | 3,000       | $c \bar{c}$            |
|             | 3             | +1            | 2,005       | $c \bar{s}$            |
|             | 4             | -1            | 22,810      | $d \bar{t}$            |
| 2           | 1             | +1            | 620         | $u \bar{d}$            |
|             | 2             | -1            | 6,500       | $b \bar{c}$            |
|             | 3             | 0             | 1,010       | $s \bar{s}$            |
|             | 4             | +1            | 5,310       | $u \bar{b}$            |
| 3           | 1             | -1            | 620         | $d \bar{u}$            |
|             | 2             | +1            | 815         | $u \bar{s}$            |
|             | 3             | +1            | 27,500      | $t \bar{b}$            |
|             | 4 *           | 0             | 620         | $u \bar{u}, d \bar{d}$ |
| 4           | 1             | +1            | 1,810       | $c \bar{d}$            |
|             | 2             | -1            | 2,005       | $s \bar{c}$            |
|             | 3             | -1            | 23,005      | $s \bar{t}$            |
|             | 4 *           | 0             | 24,000      | $t \bar{c}, \bar{t} c$ |
| 5           | 1             | -1            | 5,310       | $b \bar{u}$            |
|             | 2             | +1            | 6,500       | $c \bar{b}$            |
|             | 3             | -1            | 27,500      | $b \bar{t}$            |
|             | 4 *           | 0             | 5,505       | $b \bar{s}, \bar{b} s$ |

\* Two answers

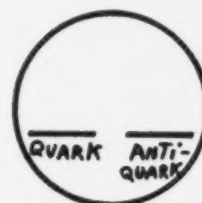
# DECODE A MESON

|                | Mass<br>MeV | Charge | Quarks |
|----------------|-------------|--------|--------|
| Charge _____   | _____       | _____  | _____  |
| Mass _____ MeV | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                | Mass<br>MeV | Charge | Quarks |
|----------------|-------------|--------|--------|
| Charge _____   | _____       | _____  | _____  |
| Mass _____ MeV | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                | Mass<br>MeV | Charge | Quarks |
|----------------|-------------|--------|--------|
| Charge _____   | _____       | _____  | _____  |
| Mass _____ MeV | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                | Mass<br>MeV | Charge | Quarks |
|----------------|-------------|--------|--------|
| Charge _____   | _____       | _____  | _____  |
| Mass _____ MeV | _____       | _____  | _____  |



Name: \_\_\_\_\_

# DECODE A MESON

|     | Charge | Mass   | Solution    |
|-----|--------|--------|-------------|
| 1.  | -1     | 620    | $d \bar{u}$ |
| 2.  | -1     | 815    | $s \bar{u}$ |
| 3.  | -1     | 5,310  | $b \bar{u}$ |
| 4.  | +1     | 620    | $u \bar{d}$ |
| 5.  | +1     | 1,810  | $c \bar{d}$ |
| 6.  | +1     | 22,810 | $t \bar{d}$ |
| 7.  | -1     | 1,810  | $d \bar{c}$ |
| 8.  | 0      | 3,000  | $c \bar{c}$ |
| 9.  | -1     | 2,005  | $s \bar{c}$ |
| 10. | -1     | 6,500  | $b \bar{c}$ |
| 11. | +1     | 815    | $u \bar{s}$ |
| 12. | +1     | 2,005  | $c \bar{s}$ |
| 13. | 0      | 1,010  | $s \bar{s}$ |
| 14. | +1     | 23,005 | $t \bar{s}$ |
| 15. | -1     | 22,810 | $d \bar{t}$ |
| 16. | -1     | 23,005 | $s \bar{t}$ |
| 17. | 0      | 45,000 | $t \bar{t}$ |
| 18. | -1     | 27,500 | $b \bar{t}$ |
| 19. | +1     | 5,310  | $u \bar{b}$ |
| 20. | +1     | 6,500  | $c \bar{b}$ |
| 21. | +1     | 27,500 | $t \bar{b}$ |
| 22. | 0      | 10,000 | $b \bar{b}$ |

|    | Charge | Mass   | Solution                    |
|----|--------|--------|-----------------------------|
| 1. | 0      | 620    | $u \bar{u} \quad d \bar{d}$ |
| 2. | 0      | 1,810  | $c \bar{u} \quad \bar{c} u$ |
| 3. | 0      | 815    | $s \bar{d} \quad \bar{s} d$ |
| 4. | 0      | 24,000 | $t \bar{c} \quad \bar{t} c$ |
| 5. | 0      | 5,310  | $b \bar{d} \quad \bar{b} d$ |
| 6. | 0      | 22,810 | $t \bar{u} \quad \bar{t} u$ |
| 7. | 0      | 5,505  | $b \bar{s} \quad \bar{b} s$ |

## DECODE A BARYON

There are two families of three quark particles: the baryons, an all quark system (qqq); and the anti-baryons, an all antiquark system ( $\bar{q}\bar{q}\bar{q}$ ). Most of the known particles are baryons. There are 56 possible baryons:

6 with 3 quarks the same.  
30 with 2 quarks the same.  
20 with all quarks different.

Example: Charge: 0

Mass: 2,315 MeV

1. The mass must be the total of 3 quarks.

|                  |        |             |
|------------------|--------|-------------|
| It must include: | c      | 1,500       |
|                  | s      | 505         |
|                  | u or d | 310         |
|                  |        | <hr/> 2,315 |

2. To determine the final quark composition the charge must be 0.

(if a u or d is present there are two possible combinations for this baryon)

|         |      |         |      |
|---------|------|---------|------|
| c       | +2/3 | c       | +2/3 |
| s       | -1/3 | s       | -1/3 |
| ---u--- | +2/3 | ---d--- | -1/3 |
|         | +1   |         | 0    |

The answer is c, s, d.

3. Go to the baryon dictionary to determine the name of the baryon and check your work against their mass and charges. Write the name of the baryon on your worksheet.

Example: Charge: 0  
Mass: 7,005 MeV

1. The mass must be the total of 3 quarks.

It must include:

|   |              |
|---|--------------|
| c | 1,500        |
| s | 505          |
| b | <u>5,000</u> |
|   | 7,005        |

2. To determine the final baryon the total charge must be 0.

(if there is no u or d present there is only one possible combination. Determine the charge to check it against the given charge)

|   |             |
|---|-------------|
| c | +2/3        |
| s | -1/3        |
| b | <u>-1/3</u> |
|   | 0           |

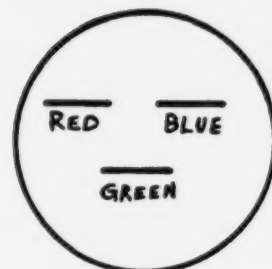
This confirms the answer is c, s, b.

3. Go to the baryon charts to determine the name of the baryon and check your work against their mass and charges. Write the name of the baryon on your worksheet.

# DECODE A BARYON

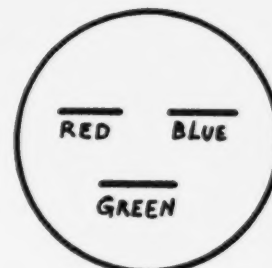
1

|                     | Mass<br>MeV | Charge | Quarks |
|---------------------|-------------|--------|--------|
| Charge <u>0</u>     | _____       | _____  | _____  |
| Mass <u>930</u> MeV | _____       | _____  | _____  |
|                     | _____       | _____  | _____  |



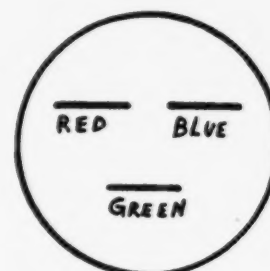
Name: \_\_\_\_\_

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>+1</u>      | _____       | _____  | _____  |
| Mass <u>3,505</u> MeV | _____       | _____  | _____  |
|                       | _____       | _____  | _____  |



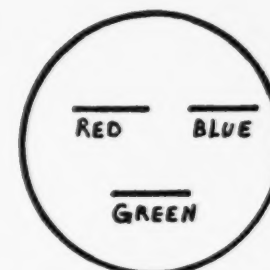
Name: \_\_\_\_\_

|                        | Mass<br>MeV | Charge | Quarks |
|------------------------|-------------|--------|--------|
| Charge <u>-1</u>       | _____       | _____  | _____  |
| Mass <u>15,000</u> MeV | _____       | _____  | _____  |
|                        | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                        | Mass<br>MeV | Charge | Quarks |
|------------------------|-------------|--------|--------|
| Charge <u>+2</u>       | _____       | _____  | _____  |
| Mass <u>24,310</u> MeV | _____       | _____  | _____  |
|                        | _____       | _____  | _____  |

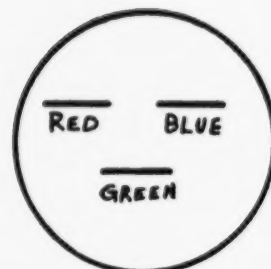


Name: \_\_\_\_\_

# DECODE A BARYON

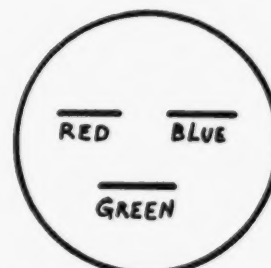
2

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>0</u>       | _____       | _____  | _____  |
| Mass <u>2,315</u> MeV | _____       | _____  | _____  |
|                       | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>+2</u>      | _____       | _____  | _____  |
| Mass <u>4,500</u> MeV | _____       | _____  | _____  |
|                       | _____       | _____  | _____  |



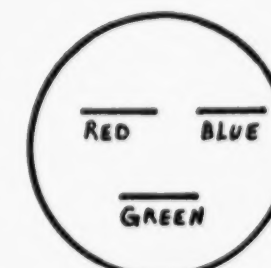
Name: \_\_\_\_\_

|                        | Mass<br>MeV | Charge | Quarks |
|------------------------|-------------|--------|--------|
| Charge <u>-1</u>       | _____       | _____  | _____  |
| Mass <u>10,310</u> MeV | _____       | _____  | _____  |
|                        | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>+1</u>      | _____       | _____  | _____  |
| Mass <u>6,810</u> MeV | _____       | _____  | _____  |
|                       | _____       | _____  | _____  |

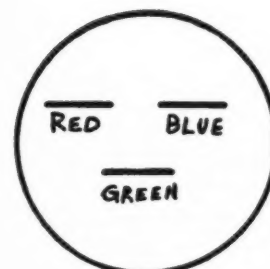


Name: \_\_\_\_\_

# DECODE A BARYON

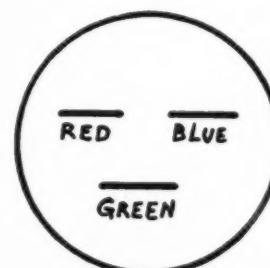
3

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>-1</u>      | _____       | _____  | _____  |
| Mass <u>1,515</u> MeV | _____       | _____  | _____  |
|                       | _____       | _____  | _____  |



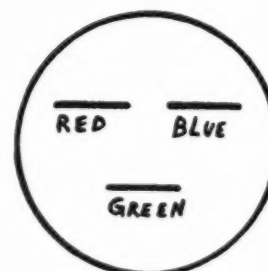
Name: \_\_\_\_\_

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>+1</u>      | _____       | _____  | _____  |
| Mass <u>2,120</u> MeV | _____       | _____  | _____  |
|                       | _____       | _____  | _____  |



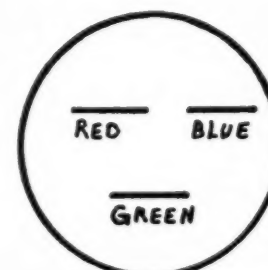
Name: \_\_\_\_\_

|                        | Mass<br>MeV | Charge | Quarks |
|------------------------|-------------|--------|--------|
| Charge <u>0</u>        | _____       | _____  | _____  |
| Mass <u>28,005</u> MeV | _____       | _____  | _____  |
|                        | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>+1</u>      | _____       | _____  | _____  |
| Mass <u>8,000</u> MeV | _____       | _____  | _____  |
|                       | _____       | _____  | _____  |

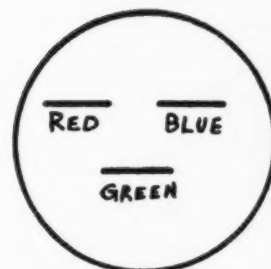


Name: \_\_\_\_\_

# DECODE A BARYON

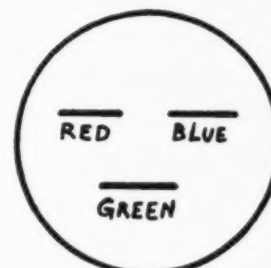
4

|                        | Mass<br>MeV | Charge | Quarks |
|------------------------|-------------|--------|--------|
| Charge <u>+2</u>       | _____       | _____  | _____  |
| Mass <u>46,500</u> MeV | _____       | _____  | _____  |
|                        | _____       | _____  | _____  |



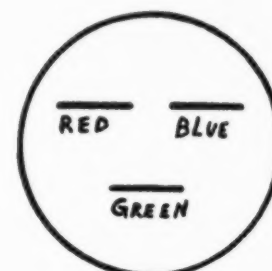
Name: \_\_\_\_\_

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>0</u>       | _____       | _____  | _____  |
| Mass <u>5,815</u> MeV | _____       | _____  | _____  |
|                       | _____       | _____  | _____  |



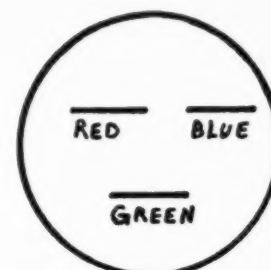
Name: \_\_\_\_\_

|                     | Mass<br>MeV | Charge | Quarks |
|---------------------|-------------|--------|--------|
| Charge <u>-1</u>    | _____       | _____  | _____  |
| Mass <u>930</u> MeV | _____       | _____  | _____  |
|                     | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>0</u>       | _____       | _____  | _____  |
| Mass <u>6,810</u> MeV | _____       | _____  | _____  |
|                       | _____       | _____  | _____  |

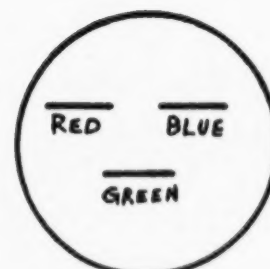


Name: \_\_\_\_\_

# DECODE A BARYON

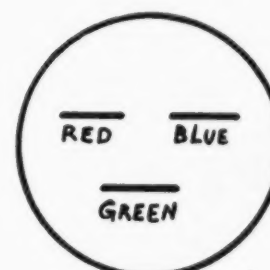
5

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>+1</u>      | _____       | _____  | _____  |
| Mass <u>2,315</u> MeV | _____       | _____  | _____  |
|                       | _____       | _____  | _____  |



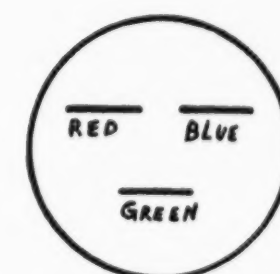
Name: \_\_\_\_\_

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>0</u>       | _____       | _____  | _____  |
| Mass <u>7,005</u> MeV | _____       | _____  | _____  |
|                       | _____       | _____  | _____  |



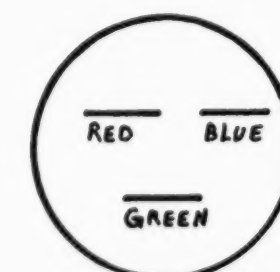
Name: \_\_\_\_\_

|                        | Mass<br>MeV | Charge | Quarks |
|------------------------|-------------|--------|--------|
| Charge <u>+2</u>       | _____       | _____  | _____  |
| Mass <u>67,500</u> MeV | _____       | _____  | _____  |
|                        | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                       | Mass<br>MeV | Charge | Quarks |
|-----------------------|-------------|--------|--------|
| Charge <u>-1</u>      | _____       | _____  | _____  |
| Mass <u>1,125</u> MeV | _____       | _____  | _____  |
|                       | _____       | _____  | _____  |



Name: \_\_\_\_\_

DECODE A BARYON

Answers to worksheets 1 to 5.

| <u>Page</u> | <u>Number</u> | <u>Charge</u> | <u>Mass</u> | <u>Answer</u> |
|-------------|---------------|---------------|-------------|---------------|
| 1           | 1             | 0             | 930         | u d d         |
|             | 2             | +1            | 3,505       | s c c         |
|             | 3             | -1            | 15,000      | b b b         |
|             | 4             | +2            | 24,310      | u c t         |
| 2           | 1             | 0             | 2,315       | d c s         |
|             | 2             | +2            | 4,500       | c c c         |
|             | 3             | -1            | 10,310      | d b b         |
|             | 4             | +1            | 6,810       | u c b         |
| 3           | 1             | -1            | 1,515       | s s s         |
|             | 2             | +1            | 2,120       | u d c         |
|             | 3             | 0             | 28,005      | s t b         |
|             | 4             | +1            | 8,000       | b c c         |
| 4           | 1             | +2            | 46,500      | c t t         |
|             | 2             | 0             | 5,815       | u s b         |
|             | 3             | -1            | 930         | d d d         |
|             | 4             | 0             | 6,810       | d c b         |
| 5           | 1             | +1            | 2,315       | u c s         |
|             | 2             | 0             | 7,005       | c s b         |
|             | 3             | +2            | 67,500      | t t t         |
|             | 4             | -1            | 1,125       | s d d         |

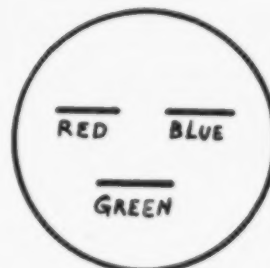
# DECODE A BARYON

|                | Mass<br>MeV | Charge | Quarks |
|----------------|-------------|--------|--------|
| Charge _____   | _____       | _____  | _____  |
| Mass _____ MeV | _____       | _____  | _____  |
|                | _____       | _____  | _____  |



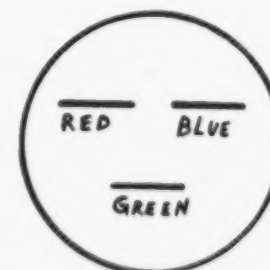
Name: \_\_\_\_\_

|                | Mass<br>MeV | Charge | Quarks |
|----------------|-------------|--------|--------|
| Charge _____   | _____       | _____  | _____  |
| Mass _____ MeV | _____       | _____  | _____  |
|                | _____       | _____  | _____  |



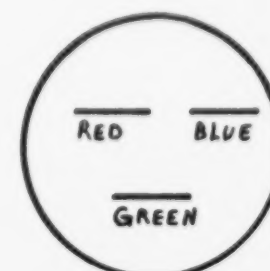
Name: \_\_\_\_\_

|                | Mass<br>MeV | Charge | Quarks |
|----------------|-------------|--------|--------|
| Charge _____   | _____       | _____  | _____  |
| Mass _____ MeV | _____       | _____  | _____  |
|                | _____       | _____  | _____  |



Name: \_\_\_\_\_

|                | Mass<br>MeV | Charge | Quarks |
|----------------|-------------|--------|--------|
| Charge _____   | _____       | _____  | _____  |
| Mass _____ MeV | _____       | _____  | _____  |
|                | _____       | _____  | _____  |

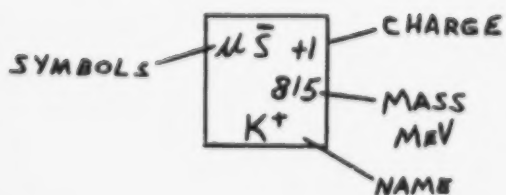


Name: \_\_\_\_\_

# MESONS

|     | $\bar{u}$                                                                                     | $\bar{d}$                                                                                         | $\bar{c}$                                                                               | $\bar{s}$                                                                                         | $\bar{t}$                                                               | $\bar{b}$                                                                                 |
|-----|-----------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|
| $u$ | $\frac{\mu\bar{u}}{\pi^0} \begin{smallmatrix} 0 \\ 620 \end{smallmatrix}$<br>RHO <sup>0</sup> | $\frac{\mu\bar{d}}{\pi^+} \begin{smallmatrix} +1 \\ 620 \end{smallmatrix}$<br>RHO <sup>+</sup>    | $\frac{\mu\bar{c}}{} \begin{smallmatrix} 0 \\ 1,810 \end{smallmatrix}$                  | $\frac{\mu\bar{s}}{} \begin{smallmatrix} +1 \\ 815 \end{smallmatrix}$<br>K <sup>+</sup>           | $\frac{\mu\bar{t}}{} \begin{smallmatrix} 0 \\ 22,810 \end{smallmatrix}$ | $\frac{\mu\bar{b}}{} \begin{smallmatrix} +1 \\ 5,310 \end{smallmatrix}$<br>B <sup>+</sup> |
| $d$ | $\frac{d\bar{u}}{\pi^-} \begin{smallmatrix} -1 \\ 620 \end{smallmatrix}$<br>RHO <sup>-</sup>  | $\frac{d\bar{d}}{\pi^0} \begin{smallmatrix} 0 \\ 620 \end{smallmatrix}$<br>RHO <sup>0</sup>       | $\frac{d\bar{c}}{} \begin{smallmatrix} -1 \\ 1,810 \end{smallmatrix}$<br>D <sup>-</sup> | $\frac{d\bar{s}}{} \begin{smallmatrix} 0 \\ 815 \end{smallmatrix}$<br>K <sub>s</sub> <sup>0</sup> | $\frac{d\bar{t}}{} \begin{smallmatrix} -1 \\ 22,810 \end{smallmatrix}$  | $\frac{d\bar{b}}{} \begin{smallmatrix} 0 \\ 5,310 \end{smallmatrix}$                      |
| $c$ | $\frac{c\bar{u}}{} \begin{smallmatrix} 0 \\ 1,810 \end{smallmatrix}$<br>D <sup>0</sup>        | $\frac{c\bar{d}}{} \begin{smallmatrix} +1 \\ 1,810 \end{smallmatrix}$<br>D <sup>+</sup>           | $\frac{c\bar{c}}{} \begin{smallmatrix} 0 \\ 3,000 \end{smallmatrix}$<br>J/psi           | $\frac{c\bar{s}}{} \begin{smallmatrix} +1 \\ 2,005 \end{smallmatrix}$<br>F <sup>+</sup>           | $\frac{c\bar{t}}{} \begin{smallmatrix} 0 \\ 24,000 \end{smallmatrix}$   | $\frac{c\bar{b}}{} \begin{smallmatrix} +1 \\ 6,500 \end{smallmatrix}$                     |
| $s$ | $\frac{s\bar{u}}{} \begin{smallmatrix} -1 \\ 815 \end{smallmatrix}$<br>K <sup>-</sup>         | $\frac{s\bar{d}}{} \begin{smallmatrix} 0 \\ 815 \end{smallmatrix}$<br>K <sub>L</sub> <sup>0</sup> | $\frac{s\bar{c}}{} \begin{smallmatrix} -1 \\ 2,005 \end{smallmatrix}$<br>F <sup>-</sup> | $\frac{s\bar{s}}{} \begin{smallmatrix} 0 \\ 1,010 \end{smallmatrix}$<br>PHI                       | $\frac{s\bar{t}}{} \begin{smallmatrix} -1 \\ 23,005 \end{smallmatrix}$  | $\frac{s\bar{b}}{} \begin{smallmatrix} 0 \\ 5,505 \end{smallmatrix}$                      |
| $t$ | $\frac{t\bar{u}}{} \begin{smallmatrix} 0 \\ 22,810 \end{smallmatrix}$                         | $\frac{t\bar{d}}{} \begin{smallmatrix} +1 \\ 22,810 \end{smallmatrix}$                            | $\frac{t\bar{c}}{} \begin{smallmatrix} 0 \\ 24,000 \end{smallmatrix}$                   | $\frac{t\bar{s}}{} \begin{smallmatrix} +1 \\ 23,005 \end{smallmatrix}$                            | $\frac{t\bar{t}}{} \begin{smallmatrix} 0 \\ 45,000 \end{smallmatrix}$   | $\frac{t\bar{b}}{} \begin{smallmatrix} +1 \\ 27,500 \end{smallmatrix}$                    |
| $b$ | $\frac{b\bar{u}}{} \begin{smallmatrix} -1 \\ 5,310 \end{smallmatrix}$<br>B <sup>-</sup>       | $\frac{b\bar{d}}{} \begin{smallmatrix} 0 \\ 5,310 \end{smallmatrix}$<br>B <sup>0</sup>            | $\frac{b\bar{c}}{} \begin{smallmatrix} -1 \\ 6,500 \end{smallmatrix}$                   | $\frac{b\bar{s}}{} \begin{smallmatrix} 0 \\ 5,505 \end{smallmatrix}$                              | $\frac{b\bar{t}}{} \begin{smallmatrix} -1 \\ 27,500 \end{smallmatrix}$  | $\frac{b\bar{b}}{} \begin{smallmatrix} 0 \\ 10,000 \end{smallmatrix}$<br>UPSILON          |

## LEGEND



K = KAON

$\pi$  = PION = SPIN 0 ( $\downarrow\uparrow$ )

42  $\rho$  = SPIN 1 ( $\uparrow\uparrow$ )

# BARYONS

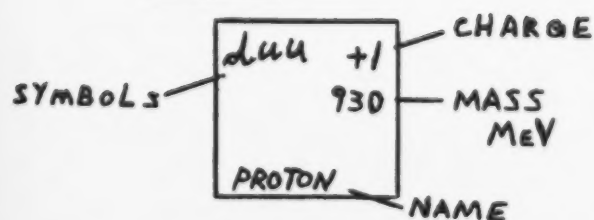
Part 1

Page 1 of 2.

Section 1 2 & 3 quarks the same.

|   | uu                         | dd                         | cc                | ss                                 | tt                | bb                |
|---|----------------------------|----------------------------|-------------------|------------------------------------|-------------------|-------------------|
| u | uuu +2<br>930<br>DELTA++   | udd 0<br>930<br>NEUTRON    | ucc +2<br>3,310   | uss 0<br>1,320<br>Xi <sup>0</sup>  | utt +2<br>45,310  | ubb 0<br>10,310   |
| d | d uu +1<br>930<br>PROTON   | ddd -1<br>930<br>DELTA-    | dcc +1<br>3,310   | dss -1<br>1,320<br>Xi <sup>-</sup> | dt t +1<br>45,310 | ddb -1<br>10,310  |
| c | c uu +2<br>2,120           | c dd 0<br>2,120            | c cc +2<br>4,500  | c ss 0<br>2,510                    | c tt +2<br>46,500 | c bb 0<br>11,500  |
| s | s uu +1<br>1,125<br>SIGMA+ | s dd -1<br>1,125<br>SIGMA- | s cc +1<br>3,505  | s ss -1<br>1,515<br>OMEGA-         | s tt +1<br>45,505 | s bb -1<br>10,505 |
| t | t uu +2<br>23,120          | t dd 0<br>23,120           | t cc +2<br>25,500 | t ss 0<br>23,510                   | t tt +2<br>67,500 | t bb 0<br>32,500  |
| b | b uu +1<br>5,620           | b dd -1<br>5,620           | b cc +1<br>8,000  | b ss -1<br>6010                    | b tt +1<br>50,000 | b bb -1<br>15,000 |

## LEGEND



Note: In looking for a baryon; remember that quark sstructure is reversible. cst is the same as cts, stc, tcs, sct, and tsc.

# BARYONS

Part 1

Section 2 all quarks are different.

Page 2 of 2.

U PRESENT

NO U PRESENT

|                          |                  |  |                  |                  |  |
|--------------------------|------------------|--|------------------|------------------|--|
| Udc +1<br>2,120          | Ucs +1<br>2,315  |  | dcs 0<br>2,315   | cst +1<br>24,505 |  |
| Uds 0<br>1,125<br>LAMBdA | Uct +2<br>24,310 |  | dct +1<br>24,310 | csb 0<br>7,005   |  |
| Udt +1<br>23,120         | Ucb +1<br>6,810  |  | dcb 0<br>6,810   | ctb +1<br>29,000 |  |
| Udb 0<br>5,620           | Utb +1<br>27,810 |  | dst 0<br>23,315  | stb 0<br>28,005  |  |
| Ust +1<br>23,315         |                  |  | dsb -1<br>5,815  |                  |  |
| Usb 0<br>5,815           |                  |  | dtb 0<br>27,810  |                  |  |

## LEGEND

|         |        |             |
|---------|--------|-------------|
| SYMBOLS | Udc +1 | CHARGE      |
|         | 1,820  | MASS<br>MEV |
|         |        | NAME        |

# anti-BARYONS

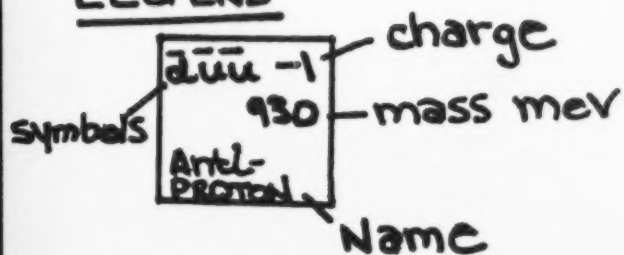
Part 2

Page 1 of 2.

Section 1 2 & 3 anti-quarks the same.

|           | $\bar{u}\bar{u}$                                 | $\bar{d}\bar{d}$                    | $\bar{c}\bar{c}$                     | $\bar{s}\bar{s}$                    | $\bar{t}\bar{t}$                     | $\bar{b}\bar{b}$                     |
|-----------|--------------------------------------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|--------------------------------------|
| $\bar{u}$ | $\bar{u}\bar{u}\bar{u} -2$<br>930                | $\bar{u}\bar{d}\bar{d} 0$<br>930    | $\bar{u}\bar{c}\bar{c} -2$<br>3,310  | $\bar{u}\bar{s}\bar{s} 0$<br>1,320  | $\bar{u}\bar{t}\bar{t} -2$<br>45,310 | $\bar{u}\bar{b}\bar{b} 0$<br>10,310  |
| $\bar{d}$ | $\bar{d}\bar{u}\bar{u} -1$<br>930<br>Anti-proton | $\bar{d}\bar{d}\bar{d} +1$<br>930   | $\bar{d}\bar{c}\bar{c} -1$<br>3,310  | $\bar{d}\bar{s}\bar{s} +1$<br>1,320 | $\bar{d}\bar{t}\bar{t} -1$<br>45,310 | $\bar{d}\bar{b}\bar{b} +1$<br>10,310 |
| $\bar{c}$ | $\bar{c}\bar{u}\bar{u} -2$<br>2,120              | $\bar{c}\bar{d}\bar{d} 0$<br>2,120  | $\bar{c}\bar{c}\bar{c} -2$<br>4,500  | $\bar{c}\bar{s}\bar{s} 0$<br>2,510  | $\bar{c}\bar{t}\bar{t} -2$<br>46,500 | $\bar{c}\bar{b}\bar{b} 0$<br>11,500  |
| $\bar{s}$ | $\bar{s}\bar{u}\bar{u} -1$<br>1,125              | $\bar{s}\bar{d}\bar{d} +1$<br>1,125 | $\bar{s}\bar{c}\bar{c} -1$<br>3,505  | $\bar{s}\bar{s}\bar{s} +1$<br>1,515 | $\bar{s}\bar{t}\bar{t} -1$<br>45,505 | $\bar{s}\bar{b}\bar{b} +1$<br>10,505 |
| $\bar{t}$ | $\bar{t}\bar{u}\bar{u} -2$<br>23,120             | $\bar{t}\bar{d}\bar{d} 0$<br>23,120 | $\bar{t}\bar{c}\bar{c} -2$<br>25,505 | $\bar{t}\bar{s}\bar{s} 0$<br>23,510 | $\bar{t}\bar{t}\bar{t} -2$<br>67,500 | $\bar{t}\bar{b}\bar{b} 0$<br>32,500  |
| $\bar{b}$ | $\bar{b}\bar{u}\bar{u} -1$<br>5,620              | $\bar{b}\bar{d}\bar{d} +1$<br>5,620 | $\bar{b}\bar{c}\bar{c} -1$<br>8,000  | $\bar{b}\bar{s}\bar{s} +1$<br>6,010 | $\bar{b}\bar{t}\bar{t} -1$<br>50,000 | $\bar{b}\bar{b}\bar{b} +1$<br>15,000 |

## LEGEND



# anti-BARYONS

Part 2

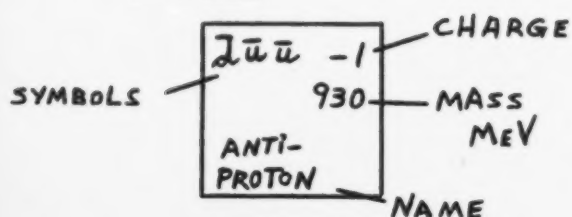
Section 2 all anti-quarks are different. Page 2 of 2.

$\bar{u}$  present

No  $\bar{u}$  present

|                                      |                                      |  |                                      |                                      |  |
|--------------------------------------|--------------------------------------|--|--------------------------------------|--------------------------------------|--|
| $\bar{u}\bar{d}\bar{c} -1$<br>2,120  | $\bar{u}\bar{c}\bar{s} -1$<br>2,315  |  | $\bar{d}\bar{c}\bar{s} 0$<br>2,315   | $\bar{c}\bar{s}\bar{t} -1$<br>24,505 |  |
| $\bar{u}\bar{d}\bar{s} 0$<br>1,125   | $\bar{u}\bar{c}\bar{t} -2$<br>24,310 |  | $\bar{d}\bar{c}\bar{t} -1$<br>24,310 | $\bar{c}\bar{s}\bar{b} 0$<br>7,005   |  |
| $\bar{u}\bar{d}\bar{t} -1$<br>23,120 | $\bar{u}\bar{c}\bar{b} -1$<br>6,810  |  | $\bar{d}\bar{c}\bar{b} 0$<br>6,810   | $\bar{c}\bar{t}\bar{b} -1$<br>29,000 |  |
| $\bar{u}\bar{d}\bar{b} 0$<br>5,620   | $\bar{u}\bar{t}\bar{b} -1$<br>27,810 |  | $\bar{d}\bar{s}\bar{t} 0$<br>23,315  | $\bar{s}\bar{t}\bar{b} 0$<br>28,005  |  |
| $\bar{u}\bar{s}\bar{t} -1$<br>23,315 |                                      |  | $\bar{d}\bar{s}\bar{b} +1$<br>5,815  |                                      |  |
| $\bar{u}\bar{s}\bar{b} 0$<br>5,815   |                                      |  | $\bar{d}\bar{t}\bar{b} 0$<br>27,810  |                                      |  |

## LEGEND



t

d

u

c

s

h

t

d

u

c

s

h